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DEFENCE RESEARCH ESTABLISHMENT OTTAWA
TECHNICAL NOTE 86-4

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ABSTRACT

Several types of dual MOSFET gamma-radiation sensors have been fabricated by Carleton University and tested by Canadian Astronautics Limited. The most promising of these types have been investigated more extensively at DREO with regards to sensitivity, stability and energy dependence.

Fifteen sensors irradiated under identical conditions, using a bias of + 5.6 V on one gate, have been found to have sensitivities within 5% of the mean value of 260 mV/Gy. This sensitivity, along with the stability found for these MOSFETs, should enable these sensors to meet the requirements for the gamma-radiation measurement of a military personal dosimeter.

Measurements with filtered x-rays indicate that the response at 100 to 200 keV is up to three times as large as at 1.25 MeV and that photon filtration is required to improve the energy response.

RÉSUMÉ

Plusieurs types de capteurs de rayonnement gamma à doubles MOSFET ont été réalisés par l'Université Carleton et testés par la Canadian Astronautics Limited. Le plus prometteur a été soumis au DREO pour une étude approfondie de sa sensibilité, de sa stabilité et de sa consommation d'énergie.

Quinze capteurs irradiés dans des conditions identiques et avec polarisation de grille de + 5,6 V ont présenté une sensibilité égale à 5% près de la valeur moyenne de 261 mV/Gy. Cette sensibilité, combinée à la stabilité constatée des MOSFET, devrait permettre l'emploi des capteurs pour la mesure du rayonnement gamma en dosimétrie personnelle militaire.

Des mesures faites avec des rayons X filtrés indiquent que la réponse entre 100 et 200 keV est jusqu'à trois fois supérieure qu'à 1,25 MeV et qu'il faut filtrer les photons pour améliorer la réponse énergétique.

1. Introduction

As part of a project to develop a personal dosimetry system for the CF, MOSFET gamma-ray sensors have been fabricated by Carleton University under sub-contract from Canadian Astronautics Limited (CAL). CAL has recently (March 1985) completed a contract with DREO.

Measurements made by CAL and by DREO have shown that to attain good sensitivity it is necessary to apply a bias to the gate of these devices during irradiation. A dual MOSFET with one gate biased and the other gate used as an unbiased reference was considered as well as the single biased device. Both single and dual MOSFETs were made by Carleton, and tested by CAL. The dual device, used differentially, has the advantage of low initial reading and compensation for changes in reading temperature. Thus it is the dual (biased/unbiased) MOSFET which is being seriously considered as the gamma-ray sensor for the CF dosimeter.

The CAL report (Ref (1)) on the dual devices gives results on four different MOSFET types, resulting from the combinations of two silicon starting resistivities and two oxide-layer thicknesses. The most promising type resulted from using the higher resistivity silicon and the thicker (0.5 μm) oxide layer. These MOSFETs had a gate-to-source operating voltage of about 7 V and a differential sensitivity of 2.5 mV/cGy. However, the CAL report includes results on only 6 of these devices.

To get a better idea of the consistency of these devices another 15 from the same 0.5-μm wafer (referred to as CAL 6), as those tested by CAL, were obtained for testing at DREO. In addition to those devices packaged by Carleton, 55 0.5-μm MOSFETs of a similar type (CAL 8) were packaged by Siltronics. This note gives the results of measurements made on these devices.

2. Test Procedure

The dual MOSFETs were mounted in sockets in the arrangement shown in Fig 1. The basic circuit for measuring the gate-to-source voltage V_{GS} is also shown in this figure. Side 2 is used as the reference with the gate tied to the drain so that the gate voltage V_{S2} is equal to the gate-to-source voltage V_{GS2}. The feedback amplifier "A" sets V_{S1} equal to V_{S2} with the amplifier output voltage equal to V_{G1}. With gate 2 grounded $V_{G1} = V_{GS12}$; this is the differential gate-to-source voltage for equal drain-to-source currents $I_{DS1} = I_{DS2}$.

The complete circuit is shown in Fig 2. The constant current sources are determined by the supply voltage +V, the 20-kΩ resistors and the bias voltages on Q_2 and Q_4. Adjustment of R_1 is used to balance the two currents which can be varied from 100 to 200 μA by varying +V from about 9.5 to 18.3 V.

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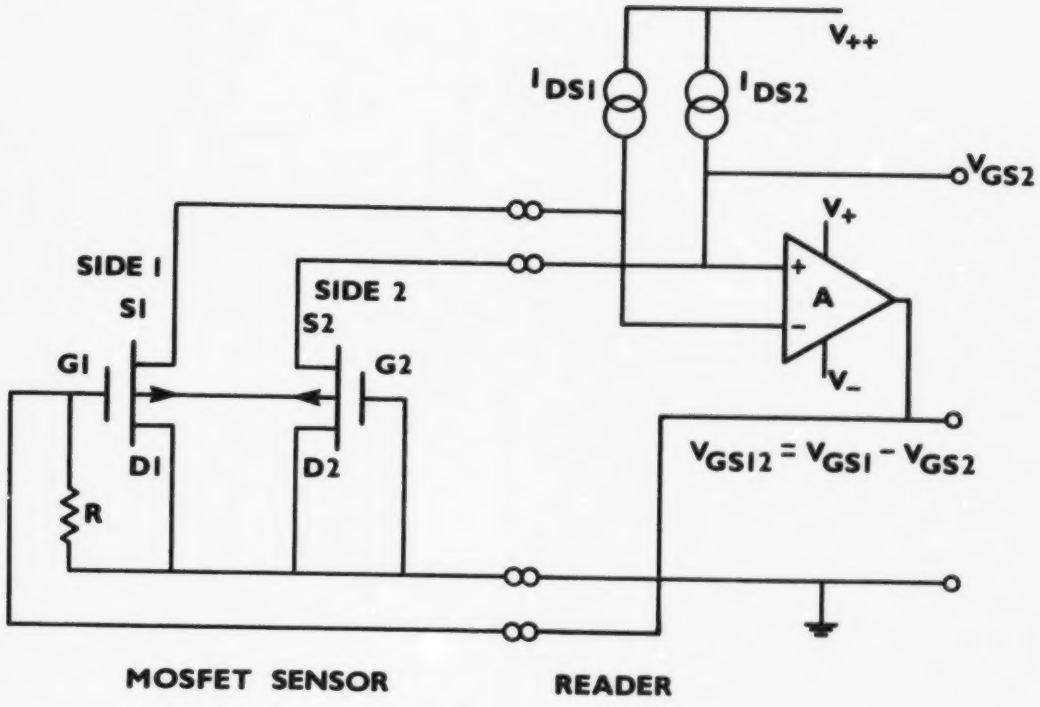

Figure 1. Arrangement in which the MOSFET sensors were usually mounted on the test boards. Connections to the basic reader circuitry are shown. During irradiation the bias voltage was normally applied to G1 relative to all other connectors in common. For some tests the bias voltage was included in series with R (10 MΩ) so that G1 was continuously under bias when not connected to the reader. "A" represents a differential feedback amplifier in the reader, which automatically sets the voltage on G1 relative to that on G2 with the source voltages differing only by the differential input voltage. I_{DS1} and I_{DS2} are balanced current sources whose magnitudes are not critical.

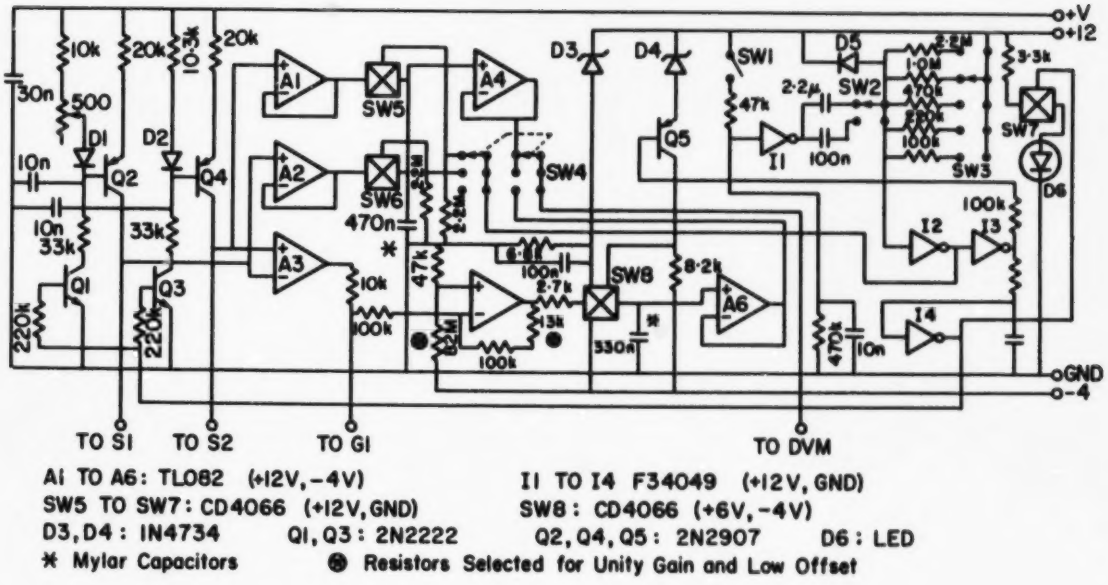

Figure 2. Circuit diagram of the reader used to measure the dual MOSFET sensors. Current pulses to the sensors are initiated by push-button SW1, the pulse length ranging from 0.01 to 5.5 s as determined by the positions of SW2 and SW3. For longer pulses, the current was kept on by grounding the input of inverter I2. During the current pulse, the mylar capacitors are charged to V_{GS} and V_{GS12} and then isolated from the MOSFET sources in the sample/hold arrangement shown. SW4 selects V_{GS} or V_{GS12} to be read by a digital voltmeter.

To study the effects of short-term drift in the readings following "turn-on" of the MOSFETs, the current sources were pulsed, simultaneously, by switching on Q_1 and Q_3 for periods determined by the time constants of the capacitors connected to switch SW2 and the resistors connected to SW3. These pulse lengths ranged from 10 ms to 5.5 s. The current pulses were initiated by push button SW1.

Amplifier A3 is the feedback amplifier (of Fig 1), the function of which was described above. To enable measurements to be made with short current pulses, the MOSFET voltages V_{GS1} (or V_{GS2}) and V_{G12} are buffered with amplifiers A1, A2 and A5 (which is also an inverter) and stored on the 470-nF and 330-nF mylar capacitors as shown. These are isolated from their buffer inputs by opening SW5, SW6 and SW8 before the current sources are removed. A4 and A6 are high-input-impedance amplifiers which buffer the mylar capacitors from the DVM which is used to read the voltages stored on the capacitors.

Buffer/amplifier A5 is also used as a unity-gain inverter. The input and feedback resistors of A5 were selected to give unity gain and to minimize the offset voltage.

During irradiations, conducted to measure the radiation sensitivity, gate 2 was usually kept connected to the drains while various voltages were applied to gate 1 relative to the drains. Measurements made with the sources and substrate floating were found to give inconsistent values for the sensitivities so that these terminals were generally connected to the drain during irradiations.

3. Initial Measurements

Initial measurements were made on all of the MOSFETs received for these tests in order to reject those which did not operate properly and to determine the initial (pre-irradiation) readings.

All 15 of the CAL6 devices (packaged by Carleton) were found to operate properly. These may have been checked previously by Carleton or by CAL. Four of the 55 CAL8 devices (packaged by Siltronics) were found to be inoperative or to operate in an unexplained manner. In addition, three of these dual MOSFETs which appeared to operate properly were found to each have one half with high gate-to-substrate leakage. Measurements made with these 7 MOSFETs are excluded from the discussions to follow.

The CAL6 MOSFETs were mounted in ceramic packages which were not hermetically sealed. The CAL6 measurements were made using a 15-V supply for the current sources (+V in Fig 2), giving source-to-drain currents of 160 μA. Initial gate-to-source voltages V_{GS} ranged from -5.92 to -6.77 V. This spread in V_{GS} is more than five times the maximum value of V_{GS12} which is the differential value of V_{GS} for the dual MOSFET.

Forty of the good 48 CAL8 MOSFETs were hemetically sealed in ceramic packages while the tops of the ceramic packages of the remaining eight were held on using epoxy. The CAL8s were measured using +V = 12 V which gives currents of 130 μA. Initial voltages V_{GSO} ranged from -7.18 to -8.23 V for the sealed MOSFETs and -6.10 to -6.57 for the unsealed devices. Presumably, the temperature used in sealing the packages had an annealing effect on the MOSFETs. As for the CAL6s, the spread in V_{GSO} for the CAL8s is much larger than the values found for V_{GS12}.

The distributions of V_{GS12} (disregarding sign) are tabulated in Table I for the CAL6 and CAL8 MOSFETs. The spread in V_{GS12} values is seen to be about the same for the two types and no difference could be seen between the sealed and the unsealed CAL8s.

TABLE I

Initial Values of Differential Gate-to-Source Voltages V_{GS12}

Range of V_{GS12} (MV)	Number of Devices			%
	CAL6	CAL8	Total	Total
0-10	2	3	5	8
0-20	4	8	12	19
0-30	6	14	20	32
0-50	6	17	23	37
0-75	7	24	31	49
0-100	11	30	41	65
0-150	14	37	51	81
0-200	15	43	58	92
0-700	15	48	63	100

For an ideal dosimeter the initial readings should be negligible in terms of the doses to be measured. Using a typical sensitivity of 2.5 mV/cGy (see below), it can be seen from Table I that half of the V_{GS12} values correspond to doses of more (or less) than 30 cGy and that a very large fraction of these MOSFETs would have to be rejected in order to start only with dosimeters which read less than 5 cGy.

The large values of V_{GS12} for these MOSFETs is not surprising considering the large variation in V_{GS} from device to device and the separation between the two halves of the MOSFET which occupies a total area of almost 1 mm x 1 mm. Decreasing these dimensions and using wafers of more uniform resistivity would undoubtedly lead to reduction in the initial V_{GS12} values.

4. Radiation Sensitivity

4.1 CAL6 MOSFET

The CAL6 MOSFETs were irradiated in a ^{60}Co field of 1 Gy/h with all terminals grounded except the gate of side 1 to which the bias voltages listed in Tables II and III were applied. All the devices were irradiated with a dose of 1.0 Gy (tissue) with the biases in Table II and with a dose of 2.0 Gy (tissue) one week later using the same biases for each MOSFET. The results of the first irradiation are listed in Table II for measurements taken just after the irradiation, after 1 day and after 1 week. Similar results for the second irradiation are listed in Table III with the period after irradiation extended to include results at one and at three months.

4.1.1 Consistency of Sensitivity

The agreement between the results for the two irradiations is very good for the individual MOSFETs. However, there is a considerable discrepancy between the sensitivities measured for the three devices at each bias. For measurements at 1 day, for example, differences as large as 17% are found in the differential sensitivity. This is somewhat larger than desirable for purposes of personal dosimetry. Hopefully, better consistency will be achieved, however, when these devices are manufactured on a commercial scale.

The measured gate-to-source voltages for both halves of device 6-4 were found to drop after a few weeks, as indicated by the low values listed in Table III for the sensitivities at 1 month, while the differential voltage remained almost unchanged. The reason for this shift in readings has not been clarified.

4.1.2 Sensitivity as a Function of Bias

The average values of the differential sensitivity at 1 day from Table III are plotted as a function of the bias voltage on gate 1 in Fig 3. While the accuray of this curve suffers from the differences between the individual devices used, the general relation between sensitivity and gate bias is shown for the 0.5-μm oxide-layer thickness. Biases between 5 and 10 V give good sensitivity which is not greatly dependent on the voltage used.

The average value of the differential sensitivity for 5.0-V bias at 1/2 h of 260 mV/Gy is in good agreement with the average value for 5 MOSFETs of 250 mV/Gy measured by CAL (Ref (1)) under similar conditions, except that CAL used currents of 410 μA. The currents used have been shown to have minimal effect on the measured sensitivity.

TABLE II

Radiation Sensitivity of CAL6 MOSFETs Irradiated by 1.0 Gray ^{60}Co
as Measured at the Stated Times after Irradiation

Device Number	Side 1 Bias (V)	Side 1 Sensitivity (mV/Gy) 1/2 h	1 day	1 wk	Side 2 Bias (V)	Side 2 Sensitivity (mV/Gy) 1/2 h	1 day	1 wk	Differential Sensitivity (mV/Gy) 1/2 h	1 day	1 wk
6-1	0.0	46	50	48	0.0	45	48	44	0.8	1.9	4.5
6-2	"	48	47.5	47	"	48	48	47	-0.2	-0.6	0.0
6-3	"	48.5	48	48.5	"	49	49	49	-0.5	-0.8	-0.5
6-4	2.5	215	232	234	"	55	66	64	161	166	170
6-5	"	232	238	247	"	49	55	54	183	183	192
6-6	"	213	214	215	"	54	58	57	159	156	158
6-7	5.0	300	300	304	"	50	56	55	250	243	247
6-8	"	315	313	316	"	49	53	51	265	259	264
6-9	"	314	329	332	"	49	55	55	264	274	277
6-10	7.5	343	334	330	"	44	47	46	299	287	284
6-11	"	339	349	353	"	45	51	49	294	298	304
6-12	"	345	339	340	"	46	49	48	299	289	292
6-13	10.0	350	338	334	"	45	45	44	305	293	290
6-14	"	396	410	409	"	66	71	68	330	339	341
6-15	"	392	400	402	"	67	71	69	325	329	333

TABLE III

Radiation Sensitivity of CAL6 MOSFETs Irradiated by 2.0 Gray ^{60}Co
One Week After the 1-Gray Irradiation of Table I, Measurements Being
Made at the Stated Times after the Second Irradiation

	Side 1						Side 2						Differential				
	Bias (V)	Sensitivity (mV/Gy)					Bias (V)	Sensitivity (mV/Gy					Sensitivity (mV/Gy)				
		1 h	1 day	1 wk	1 mo	3 mo		1 h	1 day	1 wk	1 mo	3 mo	1 h	1 day	1 wk	1 mo	3 mo
6-1	0.0	45	47	49	52		0.0	44	44	47	52		1	3	2	0	
6-2	"	44	43	46	45		"	42	42	44	41		2	1	2	4	
6-3	"	44	43	48	49		"	48	47	52	53		-4	-4	-4	-4	
6-4	2.5	213	217	230	150		"	53	57	61	-18		160	160	169	168	
6-5	"	230	234	241	246	240	"	47	55	54	54	53	183	179	187	191	187
6-6	"	214	210	211	222		"	52	52	56	58		162	158	155	163	
6-7	5.0	297	290	292	303	313	"	49	50	54	56	57	248	240	237	247	256
6-8	"	309	304	304	315	326	"	46	48	50	52	54	263	256	254	263	272
6-9	"	313	324	327	318	314	"	48	52	52	51	51	265	272	274	266	263
6-10	7.5	343	332	325	326		"	44	44	44	46		299	288	281	280	
6-11	"	340	340	352	352		"	46	48	51	51		294	292	301	301	
6-12	"	339	331	345	339		"	44	46	53	50		295	285	292	288	
6-13	10.0	355	341	335	347		"	42	40	42	48		313	301	294	299	
6-14	"	390	404	405	402	392	"	62	65	65	67	65	328	340	341	335	327
6-15	"	383	389	396	394		"	59	63	64	65		325	326	332	329	

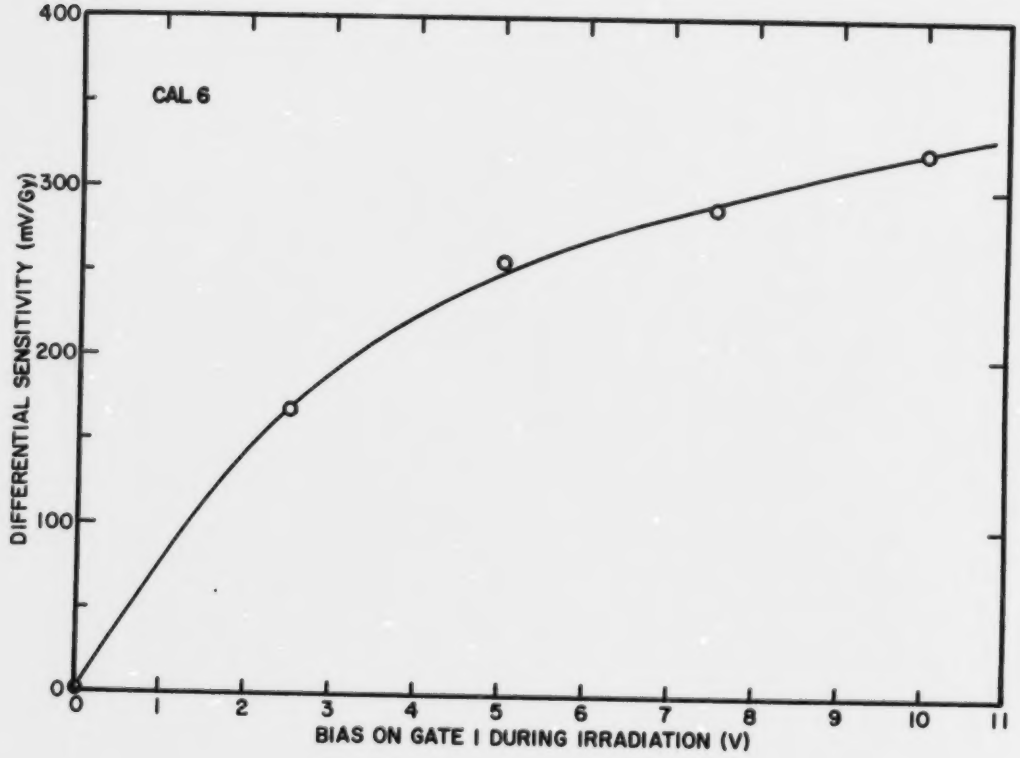

Figure 3. Differential sensitivity of CAL6 MOSFETs as a function of the bias on gate 1 (relative to all other connections in common) during irradiation. The average values from Table III one day after irradiation are used.

4.2 CAL8 MOSFET

The same irradiation field (^{60}Co at 1 Gy/h) was used for most of the CAL8 tests as was used for the CAL6 measurements. In addition some measurements were made with x-rays to investigate the effect of photon energy on the radiation sensitivity.

Irradiations were usually made with all terminals grounded except gate 1 to which various biases were applied. The effect of grounding only the drains while leaving the substrate floating is seen in Table IV, where the sensitivity of the unbiased side is increased while that of the biased side is decreased for four of the five devices with floating substrates.

4.2.1 Consistency of Sensitivity

Fifteen of the devices in Table IV were irradiated with 2 Gy of ^{60}Co gamma rays with +5.6 V applied to gate 1 and all other terminals grounded. (5.6 V is the bias supplied by two lithium/iodine cells which are being considered as the bias source for the personal dosimeter). The average differential sensitivity of these devices was found to be 261 mV/Gy with a standard deviation of 2.8% and a maximum deviation from the mean value of 5%.

This irradiation was repeated on the following day for devices 8-1 to 8-10 (see Table V) for which an average sensitivity of 253 mV/Gy was found with a standard deviation of 3.3% and a maximum deviation of 5%. The five repeat devices 8-6 to 8-10 were found to have an average sensitivity which was 3% less for the second irradiation.

4.2.2 Photon Energy Dependence

Second irradiations were also carried out on devices 8-11 to 8-19 but for these MOSFETs heavily filtered x-rays were used. The x-ray energies given in Table V are the approximate peaks of the x-ray spectra and also close to the effective energies for absorption in aluminum (Ref (2)). The radiation doses were measured using a Capintec ion chamber which required small corrections for energy dependence. The sensitivity is seen in Table V to be greatly enhanced at the x-ray energies used relative to ^{60}Co gammas. The sensitivities are larger than expected for the MOSFET materials (SiO_2, Si and Al), including the ceramic package, and may be due to high-atomic-number materials such as silver epoxy. The energy response of these devices and methods of aleviating the high response at these x-ray energies require further investigation .

TABLE IV

Sensitivity of CAL8 MOSFETs with One Gate Biased
at +5.6 V, Measured One Day after First Irradiation

Device Number	Radiation Type	Radiation Dose (Gy)	Sensitivity (mV/Gy) Unbiased	Biased	Differential
8-1	^{60}Co	2.0	100*	252*	152*
8-2	"	"	48*	316*	268*
8-3	"	"	100*	276*	175*
8-4	"	"	98*	246*	148*
8-5	"	"	97*	270*	171*
8-6	"	"	47	307	260
8-7	"	"	43	295	252
8-8	"	"	49	306	257
8-9	"	"	45	293	248
8-10	"	"	47	298	251
8-11	"	"	49	316	266
8-12	"	"	48	320	272
8-13	"	"	49	318	269
8-14	"	"	57	328	271
8-15	"	"	48	317	269
8-16	"	"	51	318	266
8-17	"	"	50	316	265
8-18	"	"	42	303	261
8-19	"	"	50	306	256
8-20	"	"	50	306	256
Average 8-6 to 8-20			49	310	261

*Substrate and Sources Floating

TABLE V

Sensitivity to Repeat Irradiation of CAL8 MOSFETs with One Gate Biased at +5.6 V. Measurements Were Made One Day after the Second Irradiation Which Followed the First Irradiation of Table IV by One Day for 8-1 to 8-10 and by One Week for the Remaining Devices

Device Number	Radiation Type	Radiation Dose (Gy)	Sensitivity (mV/Gy) Unbiased	Biased	Differential
8-1	^{60}Co	2.0	42	301	261
8-2	"	"	47	304	256
8-3	"	"	46	303	266
8-4	"	"	36	293	256
8-5	"	"	44	304	261
8-6	"	"	40	295	255
8-7	"	"	36	276	240
8-8	"	"	42	293	252
8-9	"	"	42	285	243
8-10	"	"	43	286	243
8-11	x-ray, 140 keV*	0.46	108	790	680
8-12	" , "	"	**	780	-
8-13	x-ray, 200 keV*	0.62	92	590	500
8-14	" , "	"	85	550	470
8-16	x-ray, 110 keV*	0.51	110	930	820
8-17	" , "	"	125	960	830
8-18	" , 250 keV*	"	61	510	450
8-19	" , "	"	81	540	460

Average 8-1 to 8-10

*Energy of Maximum intensity of filtered x-ray spectra

**This side of 8-12 failed, high gate-to-substrate leakage

4.2.3 Sensitivity as a Function of Bias

CAL8 MOSFETs were irradiated with 1 Gy of ^{60}Co gamma rays with biases on gate 1 ranging from -0.8 to +11.2 V. The results for sensitivities measured 1 day after exposure are listed in Table VI and plotted in Fig 4. Averages of the sensitivities at each voltage are used, excluding values for the devices which were not hermetically sealed. The unsealed devices are seen in Table VI to be about 20% less sensitive (for 5.6 V bias) than those which were hermetically sealed.

The sensitivity as a function of voltage is seen to be almost identical for the sealed CAL8 devices and the CAL6 devices, which were not hermetically sealed, for positive biases at which both types were measured. The CAL8 measurements were extended to include some negative biases. From Fig 4 it appears that the minimum response is at a very small negative bias.

5. Stability

Changes in the MOSFET gate-to-source voltage V_{GS} or in the differential voltage V_{GS12} for constant source current can result from changes in environmental factors, notably temperature. There may also be slow changes in the residual effects of radiation as charges are relocated from unstable traps. This can appear as a long-term annealing process. There may be instability in the form of drift in V_{GS} following turn-on of the MOSFET or other changes in the operating conditions. For repeatability of measurements, most readings were taken using 0.04-s current pulses as described in Sec. 2 above.

5.1 Temperature Coefficient

The temperature dependence of the MOSFET readings was investigated over the temperature range -40 to +40°C at the currents at which the sensitivity measurements were made. The measured values of V_{GS2} and V_{GS12} are plotted in Fig 5 for an unirradiated CAL8 MOSFET and for a CAL 6 MOSFET irradiated with 3 Gy ^{60}Co. The temperature coefficient should be essentially independent of the radiation dose. The very large temperature coefficients of 2 to 3 mV/°C (about 1 cGy/°C) observed here for V_{GS} can be reduced considerably by operation at the characteristic zero-temperature-coefficient current as demonstrated by CAL (Ref (3)), this current being approximately 400 μA for these MOSFETs. On the other hand, the temperature coefficient for V_{GS12} of about 0.1 mV/°C, observed here at the lower currents, is about the same as found by CAL for these devices operated at the 400 μA current. Thus, when used in the differential mode, there is no need to carefully select the current as long as the currents to the two halves of the MOSFET are well matched.

TABLE VI

Sensitivity of CAL8 MOSFETs Irradiated with 1.0 Gray of ^{60}Co Gamma Rays Using the Biases Shown, for Measurements Made 1 Day after Irradiation

Device Number	Side 1		Side 2		Differential
	Bias (V)	Sensitivity (mV/Gy)	Bias (V)	Sensitivity (mV/Gy)	Sensitivity (mV/Gy)
8-21	-0.8	90	0.0	54	37
8-51*	-0.8	63	0.0	41	22
8-22	-0.4	67	0.0	51	16
8-23	-0.4	69	0.0	51	18
8-24	+0.4	89	0.0	55	33
8-25	+0.4	91	0.0	53	39
8-26	+0.8	99	0.0	45	75
8-52*	+0.8	122	0.0	38	62
8-27	+1.4	158	0.0	53	104
8-28	+1.4	176	0.0	58	117
8-29	+2.8	256	0.0	61	195
8-30	+2.8	243	0.0	56	187
8-31	+5.6	305	0.0	48	258
8-32	+5.6	321	0.0	52	269
8-33	+5.6	358	0.0	69	289
8-34	+5.6	319	0.0	49	270
8-35	+5.6	304	0.0	44	260
8-53*	+5.6	271	0.0	42	229
8-54*	+5.6	272	0.0	42	230
8-55*	+5.6	274	0.0	48	226
8-36	+8.4	364	0.0	54	309
8-37	+8.4	270	0.0	51	319
8-38	+11.2	396	0.0	57	339
8-39	+11.2	381	0.0	56	325

*These MOSFETs were not hermetically sealed

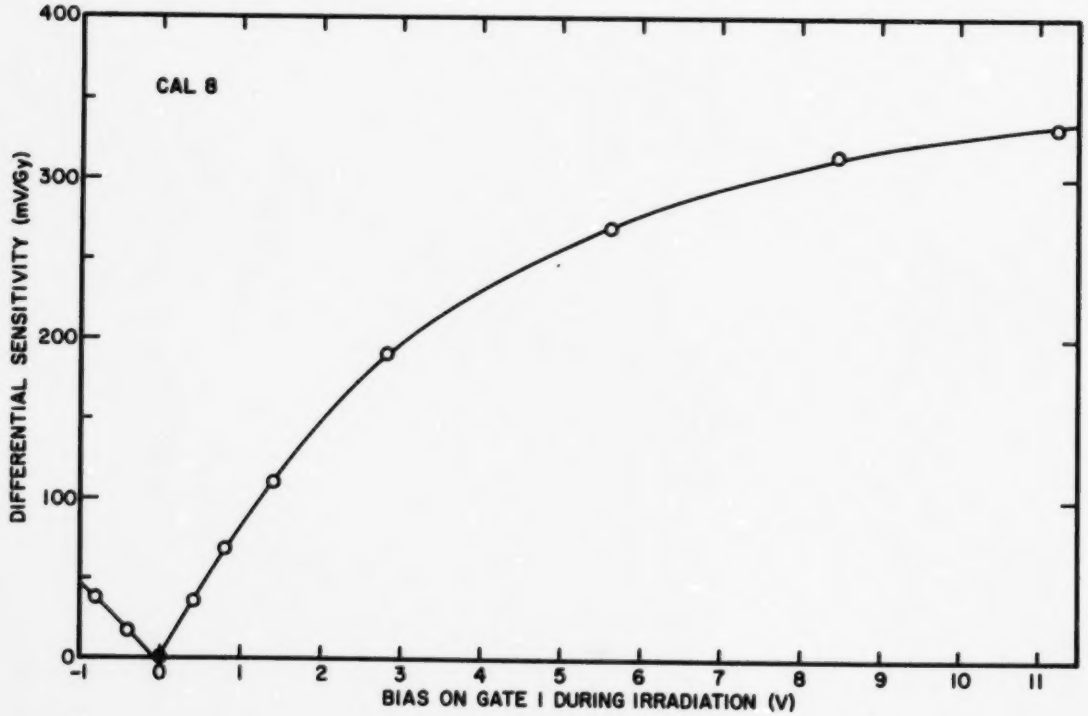

Figure 4. Differential sensitivity of CAL8 MOSFETs as a function of bias on gate 1 during irradiation. The average values from Table VI are used, excluding the unsealed devices. The curve appears to go negative at a bias voltage which is slightly negative. The relation is seen to be essentially the same at positive bias as for the CAL6s in Figure 3.

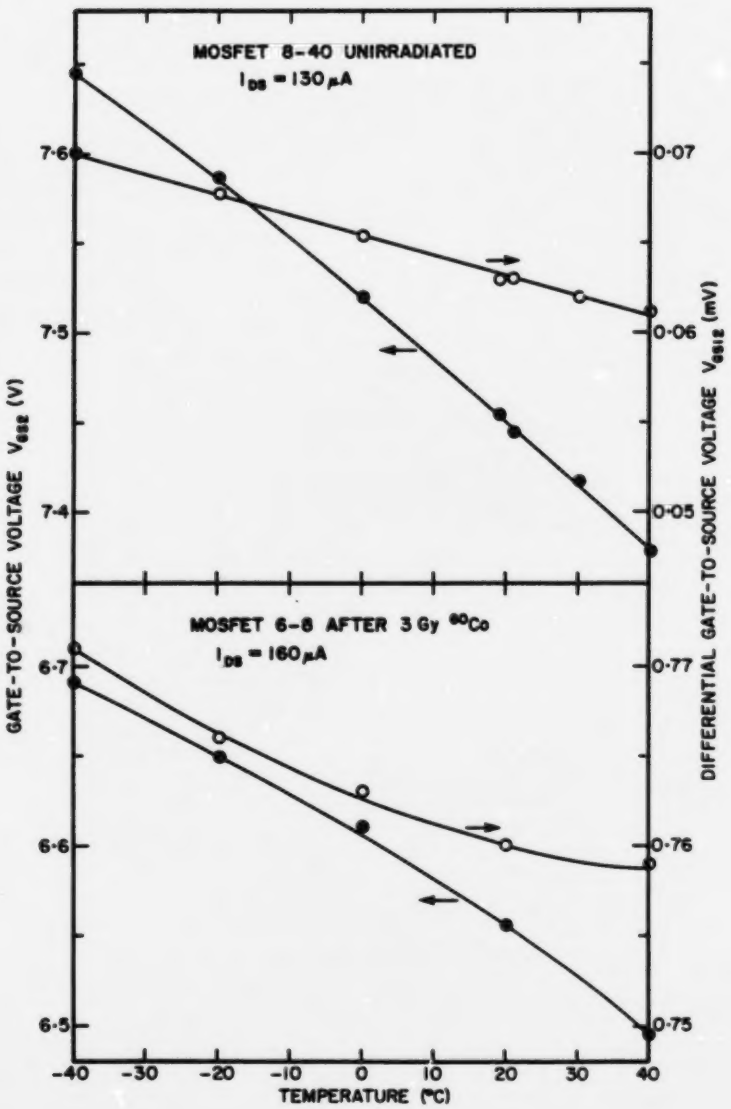

Figure 5. Dependence of gate-to-source voltage V_{GS2} and differential gate-to-source voltage V_{GS12} on reading temperature for one of each of the CAL6 and CAL8 MOSFETs. Note that the scale is expanded ten times for V_{GS12}. The change in V_{GS} with temperature can be reduced greatly by using the zero-temperature-coefficient current for the individual device. The change in V_{GS12} over the temperature range -40 to +40°C corresponds to a dose of about 4 cGy. This may be further reduced by better matching of the two halves of the dual device.

5.2 Drift in Reading

The readings for both the CAL6 and CAL8 MOSFETs were observed to remain constant when taken prior to irradiation. That is, the values of V_{GS} and V_{GS12} were found to be essentially independent of the length of the current pulse. However, the readings of irradiated units were observed to drift steadily when these MOSFETs were kept on. Fig. 6 shows the drift in the readings for MOSFET 8-7, which was irradiated with 5 Gy ^{60}Co, when it is turned on following storage for several hours with all the terminals at the same potential. Current pulses were, of course, used for the readings at times less than five seconds. This drift pattern was not altered appreciably by storing the MOSFET with +5 V on gate 1.

Fig 6 shows drifts in V_{GS} and V_{GS12} which are proportional to the logarithm of the time that the device is turned on for times from 0.01 s to 1/2 h. A factor of 10 in time results in a change of V_{GS12} of about 10 mV.

This drift in the reading represents only a few per cent of the radiation-induced voltage shift and most of this shift relaxes within a few minutes of turning off the MOSFET. Most of the effect is alleviated by taking the readings using short current pulses. However, this drift is an undesirable feature which can introduce small errors if repeated readings are taken. As the physical cause of this drift has not been identified, it cannot be predicted whether or not an improvement could result from redesign of the MOSFET.

5.3 Post-Irradiation Drift

While radiation-induced effects in MOSFETs, notably positive charge trapping in the oxide layer, are reasonably permanent in nature at normal ambient temperatures, some changes in the readings are normally observed for extended periods following irradiation. Several samples of both CAL6 and CAL8 MOSFETs were monitored for up to three months following irradiation. The readings are plotted for two CAL6s in Fig 7 and for two CAL8s in Fig 8. These readings were taken after a 2-Gy irradiation which followed a 1-Gy exposure by one week so that some influence of the earlier exposure is included.

The readings in Fig 7 and Fig 8 were taken using 0.04-s current pulses to minimize errors due to reading drifts as discussed in Sec 5.2. However, this effect may still be responsible for some scatter in the readings, in addition to scatter introduced by variations in temperature as discussed in Sec 5.1.

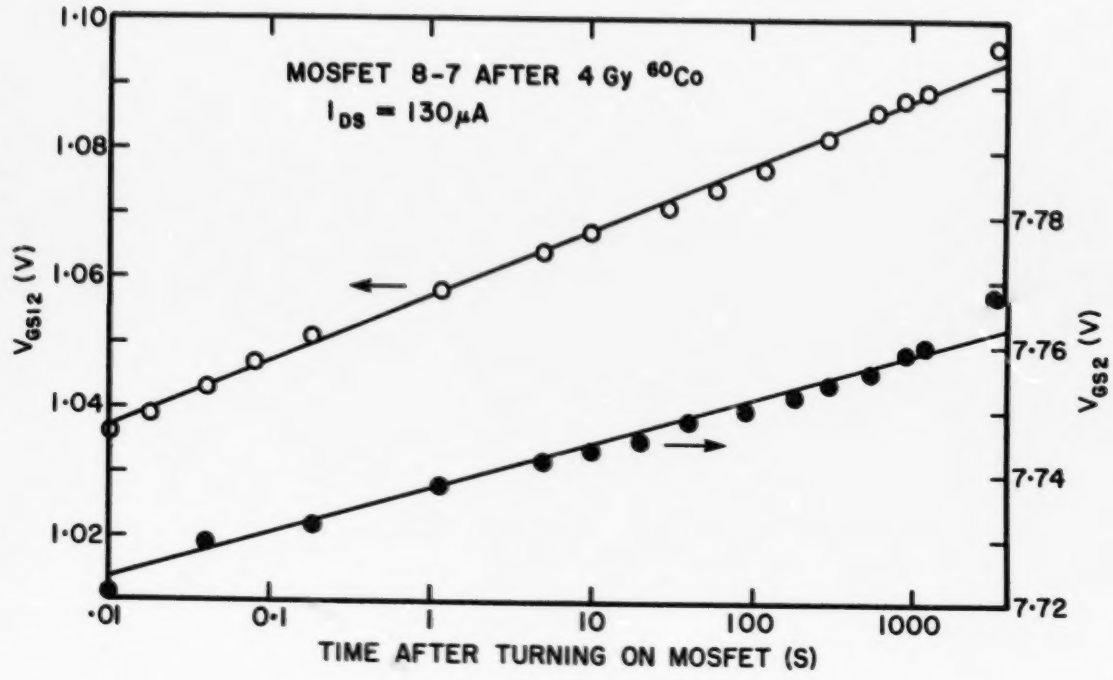

Figure 6. Typical drift in the readings of the irradiated MOSFETs following "turn-on". This drift is very small for unirradiated devices, but it can be seen that errors of a few per cent are introduced when irradiated devices are measured. These errors are minimized by using short current pulses.

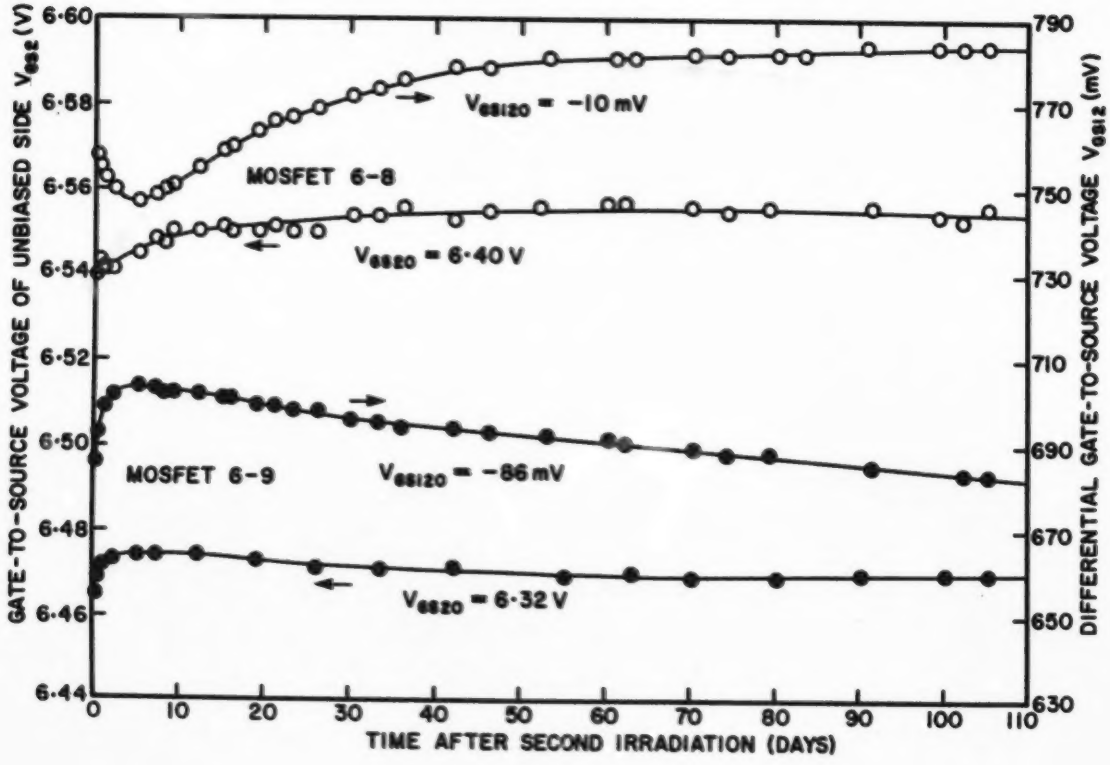

Figure 7. Two distinctly different post-irradiation drift patterns were observed for the CAL6 MOSFETs as shown here. It can be seen that errors of a few per cent are introduced by this type of instability. Presumably devices produced under more controlled conditions would have more predictable drifts in their readings. These readings are plotted as a function of time after a 2-gray irradiation which was preceeded by one week by a 1-gray irradiation. The pre-irradiation readings (V_{GS120}, etc) are shown for each curve.

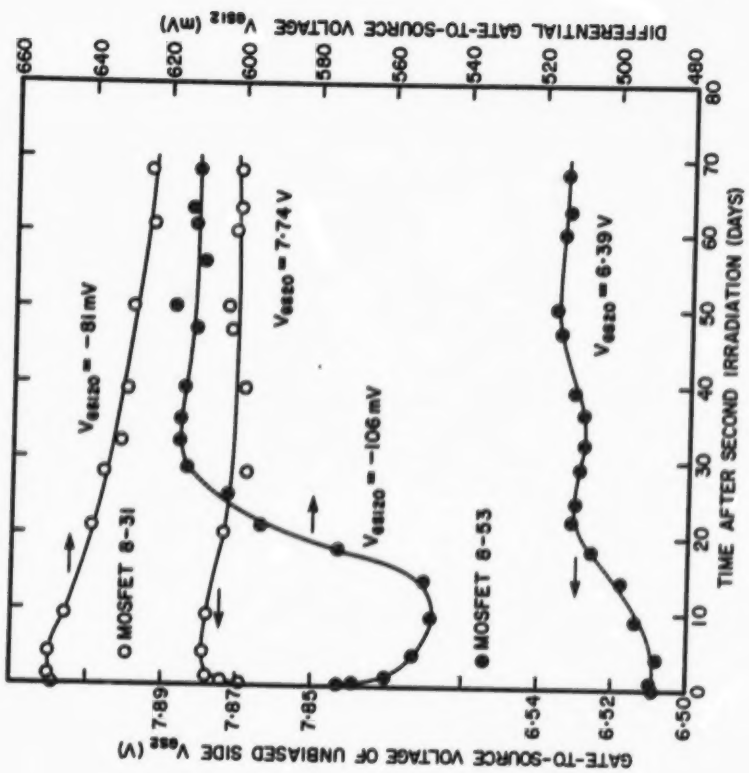

Figure 8. Typical post-irradiation drift patterns for sealed (8-31) and unsealed (8-53) CAL8 MOSFETs. Details in the Fig. 7 caption also apply here.

The drift in the CAL6s was found to follow two basic patterns as typified by the curves Fig 7. Devices numbered (in the tables) 6-6, 6-7, 6-12 and 6-13 follow similar patterns to 6-8 while 6-1, 6-11, 6-14 and 6-15 behave much like 6-9 following irradiation. Indications from CAL were that all of these samples came from the same wafer. Much more serious drift was reported by CAL (Ref (1)) for some other types of dual MOSFETs with different silicon resistivity or oxide layer thickness.

Typical drift patterns are shown in Fig 8 for the sealed CAL8s represented by 8-31 and for the unsealed CAL8s represented by 8-53. Since these patterns prevailed for the sealed and unsealed CAL8s which were monitored, it can be concluded that the difference is somehow related to either the sealed condition, which excludes moisture and oxygen, or the sealing process in which the devices are subjected to high temperature.

The post-irradiation drift of the devices measured here is generally a few per cent of the radiation-induced voltage shifts. This is comparable in magnitude to the drift observed earlier for MOSFETs (single) made by Carleton using all-dry oxide layers. (These devices were made using a dry/wet/dry oxide growth). The all-dry devices drifted consistently to increasingly larger voltage shifts whereas these MOSFETs are seen to be unpredictable in their direction of drift.

A better understanding of the causes of post-irradiation drift and the relation to the various steps in the fabrication process would suggest methods of minimizing this effect. Hopefully, controlled production by a commercial manufacturer will result in MOSFETs with post-irradiation drift which is predictably within acceptable tolerances.

6. Conclusions and Recommendations

Based on the results of measurements made at DREO and at CAL on MOSFETs produced by Carleton University, it is concluded that MOSFET gamma-radiation sensors can be produced with good sensitivity for use in a military personal dosimeter provided that a dual device is used with one gate biased at several volts. The sensitivity achieved for the dual MOSFET with 0.5- m oxide layer, having one gate biased at +5 V, is typically 260 mV/Gy. This sensitivity and the stability of these MOSFETs would enable these devices to meet the specification for the CF personal dosimetry system.

The initial differential reading of the devices produced by Carleton is too large to permit them to be used without correction, but it is anticipated that this could be reduced by redesign and by using commercial manufacturing techniques.

The photon-energy response of the Carleton devices was found to be somewhat larger than expected for the MOSFET materials, probably because of the presence of high-atomic-number materials. This problem requires further investigation to determine the required photon filtration to be included in the dosimeter package.

Using the dual device, errors due to the temperature coefficient of the reading are reduced to the equivalent of about 2 cGy and would probably be further reduced by MOSFET redesign. Short term drift in the readings, which was frequently observed after turning on the irradiated MOSFETs, can be minimized by using pulsed-current methods for reading.

The long-term drift following irradiation, which may be a form of annealing of the radiation effects in the oxide (mainly positive-charge trapping), is not well understood and has not been controlled in the fabrication of the MOSFETs at Carleton. Since the post-irradiation drift of many of the Carleton MOSFETs has been only a few per cent of the radiation-induced shift, it is not anticipated that this problem would limit the performance of devices produced commercially.

The fabrication of MOSFET gamma sensors should now be undertaken by a manufacturer with experience in MOS technology. Sufficient devices should be produced to enable statistically significant sampling to be carried out with the objective of producing devices which meet military standards. This will require extensive testing to determine the consistency of the radiation sensitivity, the limits of device stability and the photon filtration required to obtain good energy response.

7. References

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13. ABSTRACT

Several types of dual MOSFET gamma-radiation sensors have been fabricated by Carleton University and tested by Canadian Astronautics Limited. The most promising of these types have been investigated more extensively at DREO with regards to sensitivity, stability and energy dependence.

Fifteen sensors irradiated under identical conditions, using a bias of + 5.6 V on one gate, have been found to have sensitivities within 5% of the mean value of 260 mV/Gy. This sensitivity, along with the stability found for these MOSFETs, should enable these sensors to meet the requirements for the gamma-radiation measurement of a military personal dosimeter.

Measurements with filtered x-rays indicate that the response at 100 to 200 keV is up to three times as large as at 1.25 MeV and that photon filtration is required to improve the energy response.

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